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The land-water nexus of biofuel production in Brazil: Analysis of synergies and trade-offs using a multiregional input-output model

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A B S T R A C T

Biofuels play a critical role in the Paris Agreement to help achieve climate change mitigation targets. However, a significant increase in production of biofuels might potentially be realized at the expense of overusing natural resources, particularly land and water. Understanding the tradeoffs between the impacts on land and water arises as a critical issue in the development of biofuels. This energy-*water-land nexus* might be particularly important for Brazil, which currently is the world's second largest producer and the largest exporter of biofuels. Furthermore, Brazil itself has set up its own Intended Nationally Determined Contribution agenda with a significant growth of biofuel production (18%) by 2030. Most studies on environmental impacts of biofuel production have either focused on land use or water use, but very few studies assessed both. Using an environmentally extended multiregional input-output (MRIO) approach, this study analyzes the current water-land nexus of bioenergy production in Brazil by quantifying the distribution of tradeoffs and synergies between land and water use for bioethanol production and its environmental consequences across Brazilian states. Our results show a clear tradeoff of water and land impacts and significant differences between irrigated and rainfed ethanol production. When including water and land scarcity in the analysis, the results are significantly different, uncovering very different tradeoffs and synergies between bioethanol producer and consumer states that could inform the expansion of bioenergy in Brazil. Compared to other crops, sugarcane has a higher comparative advantage relative to land than to water.

1. Introduction

Biofuels play a critical role in the international agreements for climate change mitigation as the Paris Agreement was signed by the “parties” in 2016 and translated into the Intentional Nationally Determined Contributions (INDCs) pledged by the signatory countries. The synthesis of biofuels from plant biomass (mostly food crops) offers an alternative to fossil fuels (Mosedale, 2008). According to the International Energy Agency (IEA), a major opportunity to reduce fossil CO_2 emissions is the transition to renewable energy sources such as biomass from forests or agricultural crops (Kraxner et al., 2013).

However, a significant increase in production of biofuels might potentially be achieved at the expense of other natural resources, particularly land and water (Fargione et al., 2008). A number of studies have investigated these impacts. For example, Fisher et al. (2009) studied the nexus of biofuels and food security and found

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that global expansion of first-generation biofuels will threaten food security in developing countries. In this context, a number of relevant questions have emerged such as how many people could be fed by the crops used for biofuels; the extent to which these crops, if used for food consumption in the producing countries, could alleviate malnutrition; and whether bioenergy production entails an important displacement of land use through international trade of feedstock or vegetable oil (Meyfroidt et al., 2013). Several recent studies on assessing the impacts of an expansion of biofuel production in Brazil found that the reduction in GHG emissions by using ethanol in the country had been at the expense of accelerated water consumption and land use. According to Nuñez et al. (2013), the potential expansion of sugarcane cultivation (a major source for biofuel production in Brazil) would lead to a conversion of 2 million hectares (ha) of cropland from pastures. Current targets of biofuel expansion could therefore result in additional deforestation, defeating one of its primary goals of contributing to climate change mitigation. Biofuel expansion may put biodiversity at risk through land conversion. Understanding the tradeoffs between the impacts on land and water arises as a critical issue (Rulli et al., 2016). While irrigated bioenergy production can reduce the pressure on land due to higher yields, associated irrigation water requirements may lead to degradation of freshwater ecosystems and conflict with other potential users of water resources (Bonsch et al., 2016).

This *water-land nexus* might be particularly important for Brazil, which currently is the world's second largest producer and the largest exporter of biofuels. Furthermore, Brazil is likely to continue to be the main supplier of biofuels to global markets, driven by international low-carbon commitments, due to its relative abundant water and land resources. Brazil itself has set up its own INDC agenda with a significant growth of biofuel production by 2030 *(INDC Document of the Federative Republic of Brazil, 2015)* ("UN, 2015).

Sugarcane is still largely produced without irrigation in Brazil. Thus, significant productivity gains could potentially be achieved with irrigation, making sugarcane economically more attractive in many regions of the country (Dalri et al., 2008; Silva et al., 2014). For example, Scarpare et al. (2016) assessed land and water use in the sugarcane expansion areas in Brazil and concluded that irrigation management has great potential for increasing yields and limiting sugarcane expansion. On the other hand, Carneiro et al. (2014) warned that regional water constraints may limit the intensification and expansion of sugarcane production. They also concluded that the conversion of pasturelands to cropland and expansion of the dedicated sugarcane areas would be larger in regions where irrigation demand is lower, such as the southeast of the country.

Most studies on environmental impacts of biofuel production in Brazil have either focused on land use or water, but very few studies assessed both. In addition, the existing ones have primarily focused on irrigation (blue) water use. A combined assessment of land use and water footprint from a "nexus" perspective, which considers the total appropriation of water (blue, green and grey water) by biofuel production vis-à-vis other water consumers and water availability is needed to provide a more comprehensive picture of the overall impacts on water. Another gap in the literature is the impact on land or land stress created through expansion or intensification of biofuel production. In general, rainfed agriculture in semiarid regions occupies more land than irrigated cultivation (Pfister et al., 2011a), and often agriculture can either expand to areas with productive natural ecosystems in humid areas or onto irrigated marginal lands (Tilman et al., 2002) increasing the stress on land resources. This is of special interest in the case of Brazil, where one of the expected areas for agricultural expansion of sugar cane for bioethanol production is the semiarid Northeast, which already faces severe water stress conditions, and where all suitable land for sugarcane production is already in use. Therefore, further expansion would have to occur in less suitable areas (Carneiro et al., 2014), or other states in the southeast or the center-west with lower levels of water scarcity but higher levels of land stress due to agricultural production. However, existing studies have not taken into account land stress when assessing land use impacts from biofuel production.

In addition, most research on land use impacts of biofuel production in Brazil focused on direct "on-site" impacts, without considering indirect impacts emanating throughout the supply chain. Muñoz et al. (2017) assessed the direct and indirect water footprint of sugarcane-based bioenergy along global and domestic supply chains. They found that richer states such as São Paulo benefited more than other states by accruing a higher share of economic value added from exporting ethanol as part of global value chains while increasing water stress in poorer states through interregional trade. Related to land (Ferreira Filho and Horridge, 2014), assessed indirect land use (ILUC) effects of bioethanol expansion in Brazil for 15 Brazilian economic regions for a 2020 expansion scenario.

Finally, to improve the understanding of the energy-water-land nexus of biofuel production in Brazil, the literature is missing an integrated assessment of land and water impacts of bioenergy in Brazil including the economic comparative advantage of producing sugarcane for bioethanol versus using the same water and land resources for the production of other crops or livestock. This is highly relevant for Brazil, a country with high geographic and socio-economic variability, to properly assess the regional distribution of economic gains in exchange for the use of natural resources for bioenergy production.

In this study, we analyze the current water-land nexus of bioenergy production in Brazil by quantifying the spatial distribution, at the state level, of tradeoffs and synergies between land and water use of bioethanol production and its environmental consequences. We apply an environmentally extended multiregional input-output (MRIO) approach to estimate the land footprint, the land stress footprint, and the interregional virtual land flows across Brazil driven by ethanol consumption and international exports. In addition, we assess the comparative advantage of sugarcane compared to other crops, livestock and forestry.

2. Methods

2.1. Environmentally extended multi-regional input-output analysis

Multiregional input-output (MRIO) analysis is a modeling approach widely used to trace environmental impacts along entire national or global supply chains. The core of MRIO modeling is an accounting procedure using regional input-output tables and interregional trade flow matrices to depict monetary flows between sectors of the interlinked economies, which can be used to reveal the whole supply chain of each sector. The environmentally extended MRIO approach has been applied in numerous water footprint and virtual water studies because of its ability to quantify direct and indirect (supply chain) water consumption of sectoral production to satisfy final demand at regional, national or global scales (Cazcarro et al., 2013; Dietzenbacher and Velazquez, 2007; Feng et al., 2014; Hubacek and Sun, 2005; Lenzen et al., 2013; Serrano et al., 2016; White et al., 2018). MRIO has also recently been applied to study the resource nexus ((Fang and Chen, 2017), (Munoz et al., 2017) (Fang and Chen, 2018) (White et al., 2018)).

Using MRIO analysis, we calculated production- and consumption-based land footprints (LF) and scarce land footprints

(SLF) of bioethanol and associated virtual land flows associated with inter-regional and international trade. The scarce land footprint is the land footprint weighted by land stress in a catchment (aggregated to the state level). This provides a land stress weighted footprint that reflects the potential local environmental impacts of land use (Pfister et al., 2009). Through this analysis, we explored the comparative advantage of using land to produce sugarcane (the major crop for biofuel production in Brazil) versus other agricultural crops and other economic sectors across Brazil. We applied the MRIO approach to assess virtual land flows across 149 sectors and 27 Brazilian states.

To calculate virtual land flows (**VL**), we extended the MRIO model for Brazil as follows:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}(\mathbf{y} + \mathbf{e}) \quad (1)$$

where **x** is a vector of the gross output of all economic sectors across 27 Brazilian states (149 sectors in each state); **I** is the identity matrix; $\mathbf{A} = \mathbf{Z}/\widehat{\mathbf{x}}$, is the input coefficient matrix describing inputs from all sectors into the production of economic sectors to produce one unit sectorial output; **Z** is the intermediate input matrix and the hat symbol denotes the diagonalization of gross output vector **x**; $(\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix which captures total input requirements (i.e. including upstream requirements) to produce one unit of final consumption of a product; **y** is the total final consumption vector for each Brazilian state, including final demand sectors such as household consumption, Government expenditure, capital formation, and change in inventory; ***e*** is the international export vector.

To estimate land appropriation in intra- and inter-regional supply chains to satisfy final consumption and international exports in each state, we extended the MRIO framework with a land coefficient vector **k,** which represents both non-weighted land use coefficient and land stressed-weighted land use coefficients (accounting for stressed land as an indicator of land quality). To distinguish the consumptive land and land stress-weighted consumptive land, we refer to them as land and stressed land, respectively.

Thus, we derive a land multiplier matrix, which can be used to calculate total virtual land flows in Brazil:

$$\mathbf{VL}_{\boldsymbol{dom}} = \widehat{\mathbf{k}}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} \quad (2)$$

where $\mathbf{VL_{dom}}$ is a matrix containing virtual land flows from all economic sectors of Brazilian states to satisfy their own final consumption and other states' final consumption through intra- and inter-regional supply chains; $\widehat{\mathbf{k}}$ is a matrix with land coefficients on its diagonal; $\widehat{\mathbf{k}}$ may be used as the land coefficient matrix for either land or stressed land; **Y** shows the inter- and intra-regional flows of goods and services from production states and sectors to the final consumers in all states.

To calculate virtual land in international exports from Brazil to foreign countries, we used the international export vector **e** for each state *r* to drive the total land use requirement coefficient matrix $(\widehat{\mathbf{k}}(\mathbf{I} - \mathbf{A})^{-1})$ using Equation (3):

$$\mathbf{VL^r_{exp}} = \widehat{\mathbf{k}}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{e^r} \quad (3)$$

where $\mathbf{VL^r_{exp}}$ is a vector of virtual land from different sectors in different states that is consumed to meet the international exports in state **r**.

The total LF of each state in Brazil can be calculated by the summation of domestic virtual land flows ($\mathbf{VL_{dom}}$) from all industry sectors driven by the final consumption in each state using Equation (4).

$$\mathbf{LF} = \sum_{\boldsymbol{i}} \mathbf{VL_{dom}} \quad (4)$$

where ***i*** indicates each industrial sector in a given state.

We separated the land consumption of sugarcane production into three categories, sugar production, biofuel production, and others, using the share of each commodity category in the total sugarcane production from the MRIO table.

2.2. Comparative advantage ratio

A comparative advantage ratio was used to assess the competitiveness of sugarcane compared to other crops in terms of value added per unit of land use following a similar approach used in Munoz et al. (2017) for water use.

This ratio is expressed as follows:

$$CA_j = (VA_{sc}/ VA_{sx})/ (LF_{sc} / LF_{sx}) \quad (5)$$

Where CA_j is the comparative advantage ratio for a given state, VA_{sc} is the added value for sugar cane, VA_{sx} is the value added for the sector or crop compared with sugar cane production, LF_{sc} is the land use driven by sugar cane production, and LF_{sx} is the land use due to the production of the crop *(x).* We obtained the value added for each crop from the MRIO table. The comparative advantage framework has been used in the literature to study the comparative advantage of agricultural production related to the use of natural resources (Duchin and López-Morales, 2012).

By using this ratio, we are able to assess the land footprint of sugarcane driven by ethanol production from a broader water-land nexus perspective. We evaluated the competing uses of land with other crops, livestock or forestry sectors, focusing on total land consumption and the added value of sugarcane. We compared the production of sugarcane with other main crops cultivated in Brazil, namely rice, corn, and soybean as well as the main livestock sectors and forestry. A *CA* value larger than 1.0 indicates that the production of sugarcane in this specific state is more competitive in terms of the value added per unit of land than the production of other crops, and vice versa.

2.3. Water/land tradeoff coefficient

By using the results of the total water footprint analysis from Munoz et al. (2017), we integrated the two variables of water stress and land stress, through a water/land-use tradeoff coefficient to further understand the relation among water scarcity and land stress driven by biofuel production. Given the tradeoff among irrigated and non-irrigated sugar cane production (more irrigation water might be translated into less land use and more rainfed crops may imply higher land appropriation), we assessed it separately for blue, green and total water footprint through the use of a ratio of water to land impacts (WLR):

$$\mathrm{WLR} = \mathrm{WSF_i}/ LSF_i \quad (6)$$

Where WSF is the water scarce footprint for a given state (i) and LSF is the stressed land footprint for the same state (i); both driven by bioethanol production. This ratio has already been used in previous assessments of tradeoffs among water and land impacts, measured as resource appropriation, of crop production (Pfister et al., 2011b). Considering total crop production for bioethanol production across Brazilian states, the highest values of WLR will show higher relevance of water use compared to land use and vice-versa.

2.4. Data

We employed a 2011 MRIO table for Brazil at the state level (27 states). The MRIO tables were built using 27 Brazilian I–O tables and estimated inter-regional trade flows (Guilhoto et al., 2017). There are 149 sectors in the MRIO table, including 18 agricultural, 3 primary energy, 7 power generation, and 2 biofuel production sectors, such as sugarcane-based ethanol.

For the purpose of this study and to assess the competition for land of sugarcane production with the main land-consuming sectors, we focus on agriculture (11 crops), livestock (5 livestock subsectors) and forestry (cultivated and natural) sectors of the MRIO table. We used data from the National Census of Agriculture (IBGE, 2009) available for 330 crop types, which we aggregated to the state level to match the sectorial resolution of the MRIO model.

For the calculation of land stress, we used the land stress index database from ETH Zurich (Pfister et al., 2011b), which was aggregated to the state level to match our MRIO model. Land stress related to crops, measured in m^2 yr land-equivalents (m^2 yr_{eq} kg $^{-1}$), is a an indicator of land quality, which quantifies loss of natural, productive land in equivalents of the globally most productive areas and is calculated for each grid cell (Pfister et al., 2011b).

Similar to water-use related environmental impacts, the impacts due to land occupation vary regionally. Quality of land is a complex concept, comprising a range of ecosystem services. There is no consensus on one single indicator to express land quality. We use the one proposed by Pfister based on the use of net primary productivity (NPP; kg C m-2 yr-1) of the natural reference vegetation as a proxy for potential and quality. This Land Stress Index (LSI) is calculated globally at a resolution of $0.5 \times 0.5°$.

Water consumption accounts used for MRIO analysis were taken from the authors' previous study *Uncovering the Green, Blue, and Grey Water Footprint and Virtual Water of Biofuel Production in Brazil: A Nexus perspective* (Munoz et al. 2017) where water intensity of different crops was collected from the Water Footprint Network (https://waterfootprint.org/en/).

2.5. Limitations of our approach

All the recommendations provided in this study are based on a state-level analysis of land and water footprint and thus our approach presents a first step toward necessary more detailed assessments at sub-state levels (i.e., watersheds or municipalities) that will have to consider local socioeconomic and environmental contexts. For instance, special attention should be paid to areas in the Amazon basin or in the Mata Atlântica eco-region, both with high levels of environmental sensitivity given their unique values of biodiversity, and which are already critically stressed by human disturbance.

Our results provide a basis for a state-level comparison of water and land use associated with bioethanol production, which can help to compare, from a national strategic planning perspective, the environmental impacts of intensification and expansion scenarios of bioenergy in the future and to decide upon where investments in sugarcane production could be more reasonably allocated. However, an improvement of the resolution of our modeling framework is needed to downscale the analysis to sub-state or basin levels in order to provide a more detailed assessment that may support decision-making on water-or-land-resource management strategies for biofuel production at such spatial scales to effectively address scarcity of water or land.

Another area of improvement for our approach would be the quantitative determination of the tipping points for land stress values. Since our results are based on a comparative assessment of land and water stress values for sugarcane production, these tipping points are not relevant for our study but might be needed for further analysis of land stress associated with scenarios on expansion of bioethanol production.

3. Results

3.1. Land and land stress footprints and inter-regional virtual land flows of bioethanol production

In 2010, the total land footprint of sugarcane production in Brazil was 10 million hectares according to our estimate; 64% of this land use was for sugar production, 24% for ethanol production, and "other" economic sectors were responsible for 12% of total land use for sugarcane production (Fig. 1).

In the same year, 716 thousand ha were embodied in inter-regional trade across Brazil driven by ethanol production, which accounted for 29% of its total land use. From Fig. 1 we can see that São Paulo, as the top producer of bioethanol, is the largest exporter of virtual land associated with biofuel to other Brazilian states, followed by other traditional agricultural states in central and southeastern regions such as Goiás, Mato Grosso, Mato Grosso do Sul, and other states in the semiarid Northeast such as Pernambuco and Alagoas. All of them are today under moderate to severe land stress; especially in the case of Mato Grosso do Sul, Mato Grosso, Goiás, and São Paulo. At the same time, Rio de Janeiro, with lower levels of land stress, is the largest importer of virtual land. This can be explained by the fact that most of the production in São Paulo state is rainfed, while more than half of the irrigated sugarcane production (and therefore less land–intensive) occurs in the dry Northeast (Carneiro et al., 2014).

In order to verify this positive relationship between rainfed sugarcane production and land use, and between land use and water consumption, we compared our results with the results for green and blue water footprint of bioethanol production from Munoz et al. (2017). We found a high correlation (0.99) between the green water footprint and the land footprint of bioethanol while blue water footprint and land footprint show a slightly lower correlation (0.8927), as most of water used for sugar cane production is rainfed.

In order to understand the environmental impacts of biofuel production related to land use, it is key to incorporate land stress into the results, through the land stress footprint. In 2010, the land stress footprint of bioethanol production was equivalent to 1.6 million ha, which accounted for 63% of the total land footprint. According to our estimates, this is equivalent to 74% of the total land used in Brazil for rice production, or 10% of the area dedicated to corn, 5% of the area used for soy, 55% of the area used for beans or 80% of the land used for fruit crops (other than oranges).

Fig. 2 shows ethanol production related virtual land and virtual land stress traded across Brazilian states driven by regional final demand. When looking at the stressed land flows, we find similar spatial patterns in the virtual land and virtual stressed land flows between Brazilian states. We also observe the share of stressed land virtually traded across the country compared to total land flows. A total of 480 thousand ha of stressed land associated with ethanol production were traded across Brazil which accounts for around 30% of its total land stress footprint in the nation. This result indicates that production of bioethanol in central and southeast Brazil has imposed significant environmental impacts in those already land stressed states. Thus, an increase of biofuel production in these states through new-dedicated sugarcane crop areas would lead to significant additional impacts on local ecosystems. This increase in biofuel production could instead be achieved by efficiency gains, among others, based on expansion of irrigation. On the other hand, this might aggravate impacts on water resources,

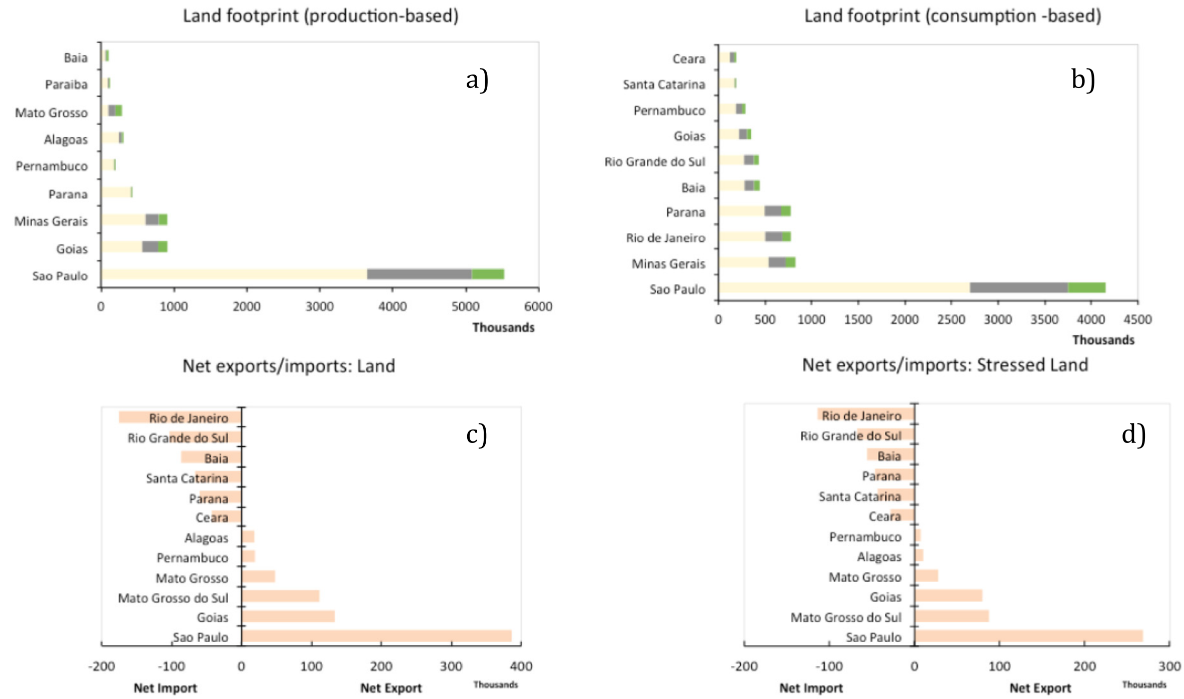

Fig. 1. Land footprint of sugarcane and net land embodied in domestic trade in Brazil (thousand ha). Above: Land footprint of sugarcane production (a) and consumption (b). Below: Top exporters and importers of virtual land (c) and virtual stressed land (d) of bioethanol in Brazil. Production-based land footprint is the land used for total sugarcane production of a given state; whereas consumption-based land footprint is the total land for sugarcane production along the entire supply chain needed to meet the final consumption of a state. Color code for a) and b): land footprint driven by sugar (yellow), ethanol (grey) and “other” sectors (green). [Units in ha].

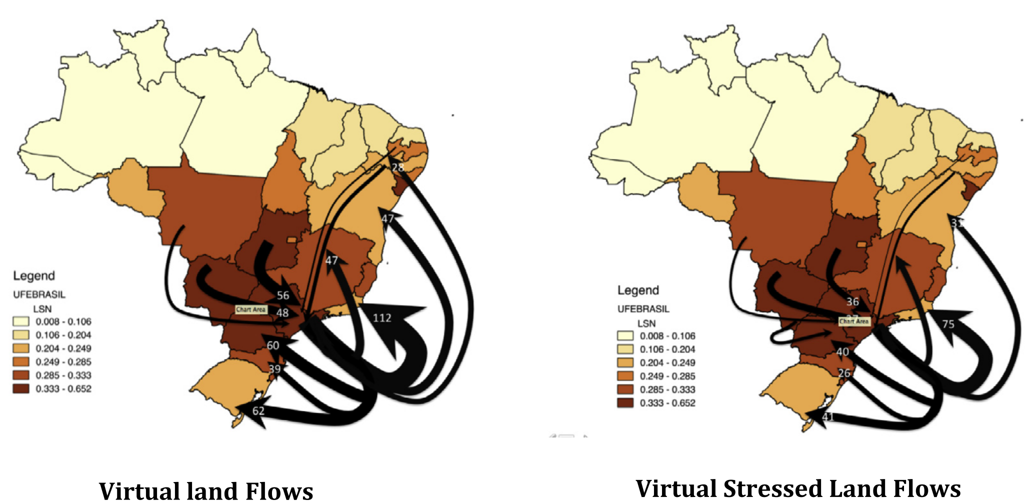

Fig. 2. Virtual flows of land and stressed land for bioethanol production across Brazilian states (units: thousand ha). Legend refers to stressed land levels for each state.

especially in water stressed states, such as Alagoas or Pernambuco, where bioethanol production is already increasing water scarcity.

3.2. Land and stressed land footprints of bioethanol production for exports

In 2010, the total land associated with ethanol production driven by Brazil's international exports to other economies was 420 thousand ha, equivalent to 17% of the total land footprint of bioethanol production, and from which only 7% were traded among Brazilian states. Compared to the green virtual water footprint of bioethanol driven by international exports (Munoz et al., 2017), which accounted for 17% of the total green water footprint of bioethanol, this number is significantly smaller.

São Paulo, Brazil's biggest economy and the top exporter in the country, is responsible for 70% of the total land footprint of bioethanol driven by Brazil's international exports and is the largest importer of virtual land from other states. São Paulo imports a total of 18 thousand ha, equivalent to 6% of its total footprint and 59% of the total virtual land traded across Brazil driven by international exports. When compared to the share of green water footprint in the same state driven by international exports (19%; Munoz et al.,

2017), the value for the land footprint is significantly lower.

The numbers above show that when compared to the water footprint, São Paulo takes up higher shares of land footprint triggered by international exports of bioethanol, as top producer and exporter of bioethanol and due to the fact that the state relies mostly upon rainfed sugarcane crop production. In other words, São Paulo is more self-sufficient in terms of land use to meet its international exports of bioethanol while it is more dependent of virtual water imports from other states for the same purpose, externalizing the environmental impacts related to water consumption (see Fig. 3).

3.3. Comparative advantage (CA) of bioethanol production considering land and water

In order to have a more comprehensive nexus perspective, we evaluated the competing uses of water and land with other crops and sectors through a comparative advantage assessment that relates the water and land footprints with the value added by different competing crops and sugarcane production. Fig. 4 shows the values of the CA assessment for sugarcane production compared to other crops relative to land use, and the results from the same assessment for blue and green water (Munoz et al. 2017). Overall, sugarcane is more productive per unit of land and unit of green and blue water than other crops.

We also find that there is an inverse relationship among CA for land use and for water footprint when we consider water and land stress. For instance, we can find lower CA advantage results relative to land use compared to green water for some land stressed states such as São Paulo and higher values of CA for land use in some water scarce states such as Alagoas. When looking at the comparison with rice, a land- and water-intensive crop, we find a competitive disadvantage (CA lower than 1.0) relative to land use in land stressed states (Mato Grosso do Sul, Mato Grosso and Paraná) while finding a competitive disadvantage for water footprint in water scarce states (Pernambuco, Alagoas and Paraíba). Bahia, a water-scarce state but with lower values of land stress compared to these states (MG, MS, PN) shows a competitive disadvantage for land use. For soy, in general, we find higher CA with regard to land use than for water, explained by soy being a green water-intensive crop (Munoz et al., 2017). In the case of corn, we find a competitive advantage for the use of green water and a competitive disadvantage relative to water footprint for water stressed states such as Paraíba and Pernambuco.

When doing an inter-state comparison, we find that the only states in which we find a lower CA for land than for water compared to all crops are São Paulo and Pernambuco. This is an interesting finding given the fact that São Paulo is the largest producer of sugarcane and bioethanol in the country at the expense of a high occupation of land for rainfed sugarcane production. In other words, in São Paulo the use of land for sugarcane production is less cost-effective, expressed in economic added value per unit of resource use (ha of land or m^3 of water), than the use of water when compared to other crops. However, this local impact on the state's land resources is compensated at the same time by São Paulo importing large amounts of virtual land from other states; and thus, externalizing the impact to other states while keeping the largest share of value added (Munoz et al. 2017).

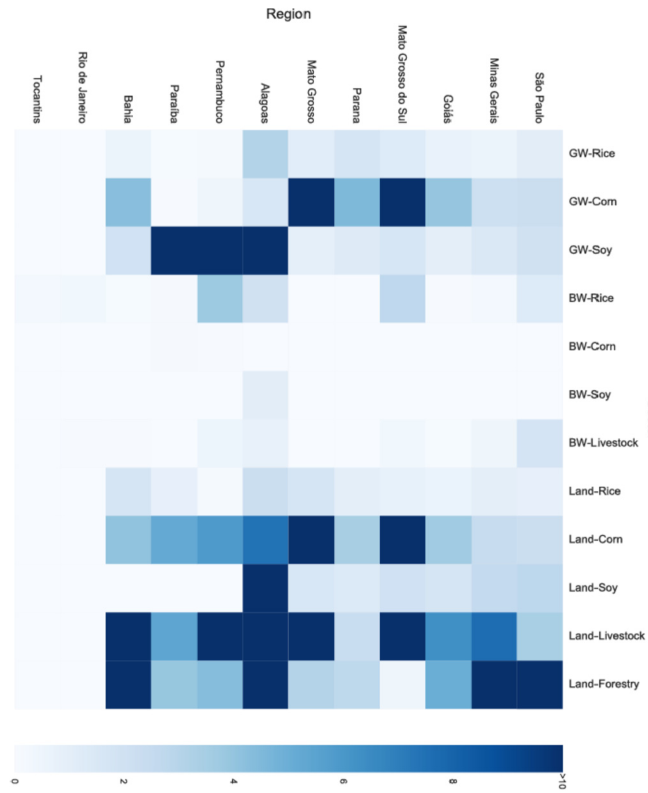

Fig. 4. Comparative Advantages assessment of sugarcane production versus other crops relative to land and water use. Note: GW is green water; BW is blue water.

3.4. Stressed land versus scarce water: trade-offs and synergies

The water/land tradeoff ratio in equation (6) has already been used in previous assessments of trade-offs among water and land impacts (measured as resource appropriation) of crop production (Pfister et al., 2011a). The results of the application of this ratio at the state level are mapped in Fig. 5. We also plotted the results for the total water footprint versus land footprint of bioethanol production for both freshwater to total land and scarce water to stressed land in order to obtain a graph by which trade-off and win-win outcomes can be readily identified. The first immediate general finding from this analysis is that the relationship among land and

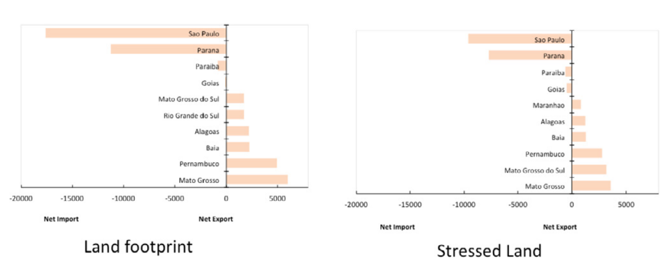

Fig. 3. Top exporters and importers of land and stressed land driven by international exports from Brazil to global markets of bioethanol [Units in ha].

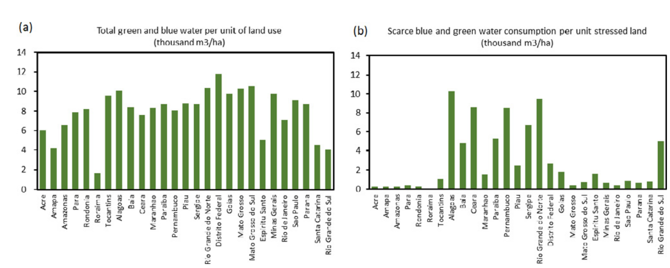

Fig. 5. Water footprint (million m^3) to land footprint (thousand ha) and scarce water footprint (million m^3) to stressed land footprint (thousand ha).

water use for biofuel production in Brazil changes significantly if we consider stress for both resources. The distribution presented for the results of freshwater to total land follows a clear linear pattern whereas the distribution for scarce water to stressed land is less correlated. This is explained by the positive correlation of the green water footprint (the biggest share of total water appropriation by bioethanol production) and land footprint and by the negative correlation of scarce water and stressed land in most cases.

For instance, when comparing the bar charts in Fig. 5 (a) and b) we can clearly see that there is a relative small fluctuation in the ratio (total freshwater to total land) for most states with the exception of a few states which show higher efficiency for the use of water compared to land, or in other words, where the consumption of biofuel production has comparatively higher impacts on land than on water, such as for Espiritu Santo, Roraima, Amapá, Santa Catarina or Rio Grande do Sul. However, when we focus on the bar chart for total scarce water to stressed land (see Fig. 5b), we find a large variation. There are states where the biofuel production has a greater and significant impact in terms of water scarcity, especially for the states in the Semiarid Northeast such as Alagoas (10.3 thousand m^3/ha), Pernambuco (8.5), Sergipe (6.7), Ceará (8.6 Mm^3/ha), Bahia (4.8), Rio Grande do Norte (9.5), and Rio Grande do Sul (4.9) in the South, which without considering scarcity had values lower than the average and thus showed more balanced impacts among water and land use. Goiás, the largest exporter of blue water driven by sugarcane production in Brazil (Munoz et al. 2017), shows also higher impacts on water scarcity than on land stress (2 thousand m^3/ha) but remarkably lower than for semiarid states. This is explained by higher levels of water scarcity in the Northeast, and higher land stress in Goiás, due to higher levels of land occupation driven by crop production.

Fig. 6 also shows the results of net inter-regional exporters and importers of total freshwater (blue and green water) versus total land (a) and total scarce water (green and grey) versus stressed land (b) driven by sugarcane production. By plotting the results in this way, we obtain a diagram through which we can identify clear trade-off and win-win outcomes among water and land impacts of biofuel production across Brazil. For instance, by focusing on the top-right quadrant, we can identify tradeoffs among states with higher impacts of bioethanol production on land stress (those with higher values closer to the horizontal axis), and states with lower impacts on water stress (those with higher values closer to the vertical axis); as well as by comparing the left-lower quadrant to the top-right quadrant to identify tradeoffs among net exporters and importers of land and water, i.e. the winners and losers of bioethanol in Brazil in terms of impacts on natural resources. Win-win outcomes can be found for states closer to the origin, or in other words, with low impacts on both land and water scarcity.

Again, by comparing 6(a) and 6(b), we clearly see that the story is very different if we incorporate scarcity in the analysis, with a linear distribution for total 6(a) and a non-linear distribution for 6(b). For instance, according to 6(a) (no stress), São Paulo is the largest exporter of both total water and land to other states, followed by Goiás, Mato Grosso do Sul and Mato Grosso, with all of them having balanced values for the use of both resources (all of them situated along the diagonal axis). Rio de Janeiro is the top importer of both land and water from other states, followed by Rio Grande do Sul, Bahia, and Santa Catarina, also aligned across the diagonal axis. However, when looking at Fig. 6b, São Paulo is the largest exporter of stressed land due to bioethanol production, with values over 250,000 ha of stressed land virtually exported, but with lower impacts in terms of water scarce footprint; with Pernambuco being the top exporter of virtual scarce water (around 300 Mm^3), followed by Alagoas and Goais (around 150 Mm^3). Goiás, an already water and land stressed state and top exporter of virtual blue water driven by bioethanol production, displays therefore more balanced impacts in terms of both water and land resources.

When looking at the net importers of water and land (lower-left quadrant), we see that the variability in the distribution when considering resource scarcity is lower. The most remarkable exceptions are Paraná and Minas Gerais, which are virtually importing relatively more scarce water than stressed land from other states.

Maps in Fig. 7 show the results of the water-to-land tradeoff ratio at the state level for biofuel production. This ratio maps higher relevance of water use (green or blue) in red areas, and higher relevance of land use in blue areas. In other words, Fig. 7 shows in red the states where the pressure on water resources is higher relative to land use or vice versa in blue. Looking at the map, water use is in general more relevant in arid or semiarid states (northeast), but also in relatively humid areas where intense irrigation and population pressure imply high water impacts, as the case of Goiás or Rio Grande do Sul (relative to green water).

4. Discussion and conclusions

Understanding both local land and water (on-site) impacts and virtual land and water impacts traded across Brazil and its spatial distribution is key for a sustainable biofuel sector, especially in the context of ongoing international climate policy and commitments made under the Paris Agreement in 2015. The trade-offs and synergies between land and water use (the water-land nexus) of bioenergy production in Brazil and its environmental and socioeconomic consequences have to be carefully assessed to ensure that further potential bioethanol expansion and associated investments for irrigation do not aggravate the current situation of water and land stress by selecting the most suitable regions in Brazil for expanding sugarcane crop production.

We used an environmentally extended MRIO model through the incorporation of land use and land stress, to uncover the land footprint of sugar-based ethanol production in Brazil and its associated inter-regional virtual land flows spatially distributed at state level. We also quantitatively assessed the spatial distribution of trade-off and synergies between water and land use of bioethanol production and its associated environmental impacts by incorporating a water to land trade-off ratio.

This study contributes to the existing literature on research of biofuels in Brazil by disaggregating at the sector level sugarcane production into sugar, bioethanol and “other” production, in order to uncover the land footprint of biofuel production and to track the virtual flows of land and stressed land from production to consumption across the supply chains in Brazil. We also advanced the understanding by combining the water and land footprints of bioethanol and virtual flows of both water and land as well as water and land stress in Brazil to obtain the total appropriation of water (green and blue water footprint) and land by bioenergy production and its related direct and indirect environmental impacts as well as the trade-offs and synergies among water and land use of ethanol production. Our results show a clear correlation between the land footprint and green water footprint, finding not just lower levels of correlation between land footprint and blue water footprint but even an inverse relationship among them in some states; which confirms a clear trade-off of environmental impacts on water and land between irrigated and rainfed-based ethanol production. We also found that when including scarcity for both water and land in the analysis, the results are significantly different, uncovering very different trade-offs and synergies between producer and consumer states of bioethanol that could inform the expansion of bioenergy in Brazil.

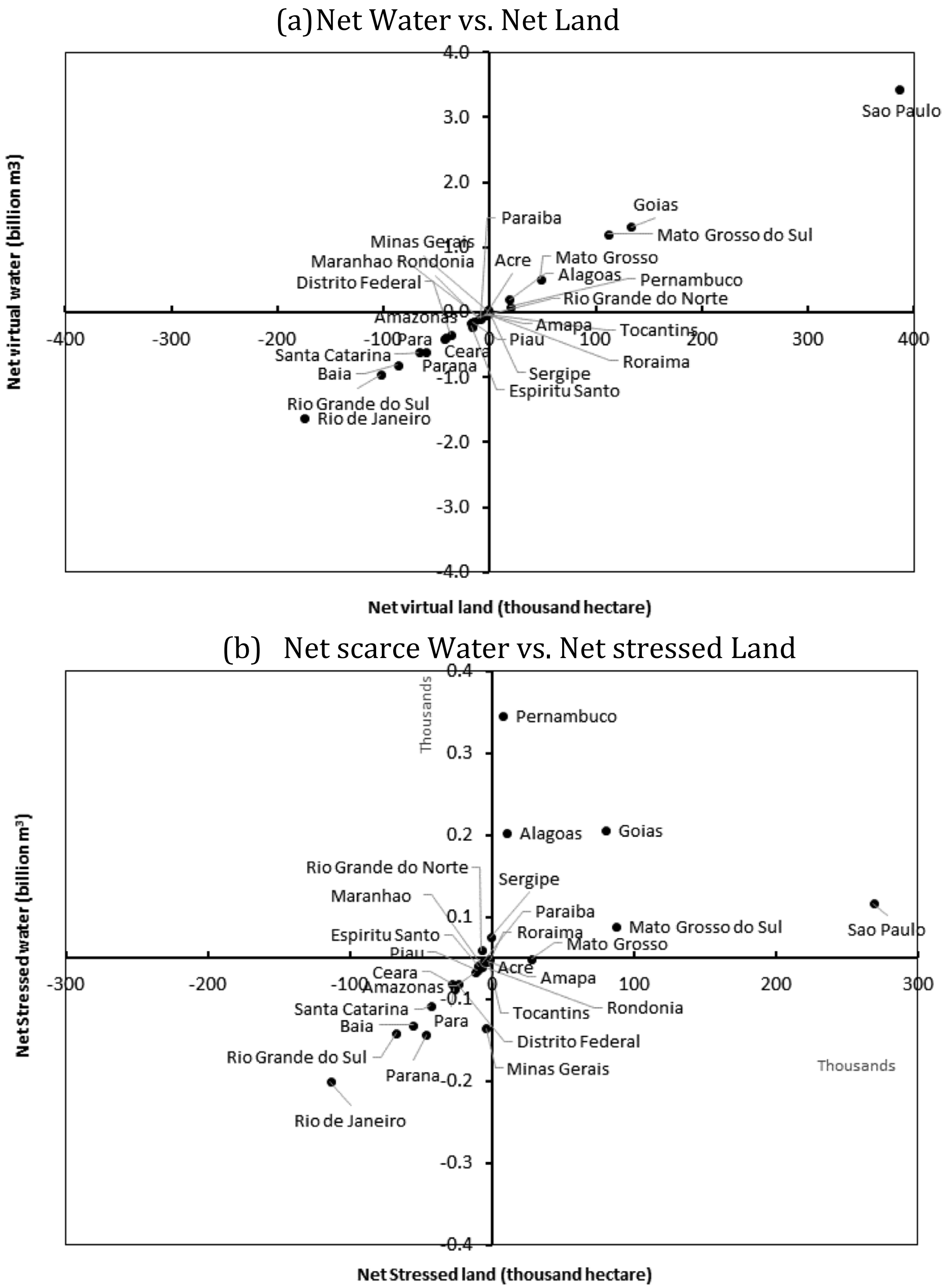

Fig. 6. Net water to net land in inter-regional trade and net scarce water to net stressed land in inter-regional trade in Brazil.

The high share of stressed land reflects the pressure that additional bioethanol production would exert on land resources in Brazil. About one third of the stressed land footprint is for export production. The spatial pattern is similar to the pattern for total virtual land flows, with São Paulo as significant virtual exporter driving imports from other land stressed states such as Mato Grosso and Mato Grosso do Sul. The situation is even more pronounced for international exports where São Paulo alone is responsible for 70% of the total land footprint driven by the production for exports from Brazil to other economies. While São Paulo is more self-sufficient in terms of land use to meet its demands from global markets for bioethanol, it is more reliant on virtual water imports from other states to meet export demand.

Our CA analysis confirms that the use of land for production of sugarcane in some states, such as São Paulo, is less cost-effective (less economic added value in return per unit of land used) than

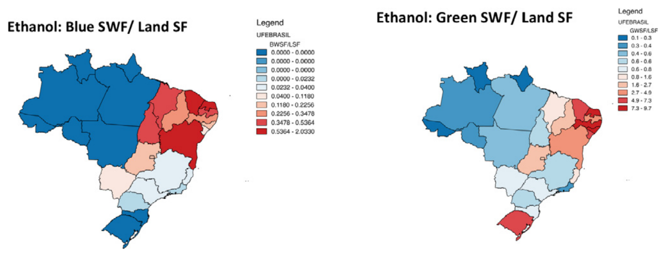

Fig. 7. Land/water trade-off ratio mapped at state level.

the use of water. However, São Paulo compensates this local impact by importing virtual land from other states to meet its local demand and international export of biofuel while keeping the largest share of value added in exchange; 85% of the value added by international exports from Brazil remains in São Paulo (Munoz et al. 2017).

Finally, we analyzed the spatial distribution of tradeoffs and synergies between land use and water consumption in Brazil for biofuel production by the use of a water-to-land nexus coefficient. Our results show a significant change when including land and water scarcity into the analysis. We found different trade-offs and synergies for land and water use that should be considered when planning bioethanol expansion in Brazil. First, in states such as Pernambuco, Alagoas, Sergipe and Paraíba, development of biofuel may lead to an increase in water scarcity but less impact in terms of land stress. In these regions, the expansion of biofuel production could rely on expansion of rainfed cropland or by investments in irrigation efficiency for existing irrigated sugarcane fields. The feasibility of the first option (expanding rainfed sugarcane fields) would have to be further investigated since the Northeast Region has already limited capacity for expanding arable land [7]. Second, some states show an increasing impact on land resources but smaller impact on water scarcity for biofuel expansion. These states are São Paulo, Mato Grosso, and Mato Grosso do Sul. In such regions, expanding bioethanol production should be supported by investments to increase irrigated cropland already dedicated to sugarcane in order to increase productivity gains rather than expanding rainfed sugarcane production, and thus increasing its land occupation. Third, there are relatively small impacts on both water scarcity and land stress from further expansion of biofuel production: These states would be the best candidates for further sugarcane development if the climate was suitable for that purpose.

Obviously, other limitations should be carefully considered, especially those concerning environmental restrictions related to land use change (for instance, in those states located in the Amazon Basin as Amazonas, Amapá or Pará, with greater environmental sensitivity and with specific legal constraints for land occupation). In this category, we may find states such as Espiritu Santo, Tocantins, Rondônia, Maranhão and Piauí. Some states have large impacts on both land stress and water scarcity. In these states there is limited capacity for expanding sugarcane production, for either rainfed or irrigated cropping, and thus sugarcane development should not be pursued. Goiás falls within this category.

Our study confirms that to properly assess the impacts of biofuel production in Brazil on land and water and its “nexus”, their mutual synergies and trade-offs, the consideration of resource scarcity and its spatial variability is key. Therefore, governmental development policies and planning for bioenergy production at national and subnational levels need to carefully consider the trade-off between land use and water consumption and its respective impacts on both resources; and the concepts of virtual water and land as well as water and land stress may serve as suitable tools to balance such trade-offs.

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